Evolution not revolution of farming systems will best feed and green the world

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ABSTRACT

The challenge to properly feed a world population of 9.2 billion by 2050, that must be achieved on essentially currently cropped area, requires that food production be increased by 70%. This large increase can only be achieved by combinations of greater crop yields and more intensive cropping adapted to local conditions and availability of inputs. Farming systems are dynamic and continuously adapt to changing ecological, environmental and social conditions, while achieving greater production and resource-use efficiency by application of science and technology. This article argues that the solution to feed and green the world in 2050 is to support this evolution more strongly by providing farmers with necessary information, inputs, and recognition. There is no revolutionary alternative. Proposals to transform agriculture to low-input and organic systems would, because of low productivity, exacerbate the challenge if applied in small part, and ensure failure if applied more widely. The challenge is, however, great. Irrigation, necessary to increase cropping intensity in many areas cannot be extended much more widely than at present, and it is uncertain if the current rate of crop yield increase can be maintained. Society needs greater recognition of the food-supply problem and must increase funding and support for agricultural research while it attends to issues of food waste and overconsumption that can make valuable reductions to food demand from agriculture.

1. Introduction

The challenge facing global food supply during the next four decades to 2050, when the world population is expected to stabilize, is well known in scientific circles, and now in political and social circles also. A large (70%) increase in food production including 1000 Mt grain and 200 Mt meat, will be required to adequately feed a then population of 9.2 billion compared with the present 7 billion (Bruinsma, 2009). The population of currently developed countries is expected to fall slightly, so the global increase of population and food demand will essentially occur in developing countries, where 1 billion are already underfed. Any further contribution of crop production to biomass or biofuel energy and industrial chemicals will add to world crop demand. There are related issues of inequality, waste, diet and population control, but the major issue is which farming systems can provide the greater production required and save most land for nature and its other values and uses.

This article will argue that the solution is found in research and development to assist farmers to improve current farming practice, largely on existing agricultural land. These modern agricultural systems ("integrated agriculture") combine biological cycles with efficient use of external inputs to increase production through greater yield by continuously improving crop cultivars and agronomic technology. The unavoidable challenge for mankind, and for farmers in particular, is to do this in a way that protects the productive potential of agricultural land (the natural resource base) and minimizes impact on natural systems, *i.e.* "to feed and green the world". Proposals for transformation to agricultural systems of lower yield cannot contribute to greater production.

The challenge is not equally distributed throughout the world. The most vulnerable areas are in Sub-Saharan Africa (SSA) and parts of South Asia (SA) and Latin America (LA) where population is growing fastest, yields are low, and infrastructure, funds and services to provide and apply currently available technology are lacking.

2. Carrying capacity of land

Each human requires nutrition of plant, or from there, animal origin to support life, work, and leisure. The Standard Nutritional

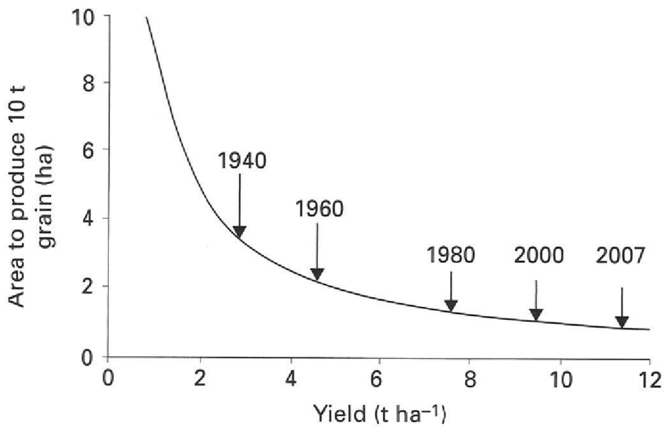

Fig. 1. Area of land required for production of 10 t grain as a function of yield per hectare. The arrows identify progression of US three-year mean maize yield, during the period 1940–2007 (Connor et al., 2011).

Unit (SNU), equivalent to annual agricultural production of 500 kg grain, is a way to measure food demand and carrying capacity of agricultural systems (Connor et al., 2011). This amount of production provides for inevitable losses in storage, seed for the next harvest, diversion of some production to fruits and vegetables, and grain to provide or complement animal diets. The importance of this number is not its absolute value, some would argue it could be smaller in some or all cases, but in its ability to provide an unambiguous link between productivity and carrying capacity of land. Thus, annual food production for 100 humans is 50 t grain equivalent that could be obtained on 50 ha at 1 t/ha but on only 5 ha at 10 t/ha. Importantly, the relationship between area required to feed a given population and yield is hyperbolic rather than linear.

The significance of this yield-area-production relationship to feeding an increasing population, and sparing land for nature (Waggoner, 1994), is seen clearly in Fig. 1 where it is related to the progression of maize yield in USA over the period 1940–2007. By increasing yield, less land is required to support a given population. On the other hand, if yield is allowed to decrease then proportionately much more land must be brought into production. So, are both options available? Greater productivity and more land?

3. Greater yield is the key to greater production

Of a total global land area of 13,000 Mha, arable land and permanent crops occupy 12% (1562 Mha) while permanent meadows and pastures occupy 26% (3406 Mha). Remaining land is forest, 3952 Mha (30%), or is unsuitable for agriculture, 4093 Mha (32%) (Nachtergaele et al., 2012). At present, most land suitable for cropping is in use, 596 Mha in developed and 966 Mha in developing countries. Total field crop production is currently about 2850 Mt, comprising 2100 Mt cereals, 140 Mt roots and tubers, 194 Mt sugar crops, 48 Mt pulses and 361 Mt oilseeds. A 70% increase would raise crop production requirement by almost 2000 Mt to 4850 Mt. Without greater yields, or further intensification of production (more crops per year), the additional land area required would be 1100 Mha.

Analysis that combines suitability of remaining land for cropping and competition for other uses, however, concludes that expansion of cropping land to 2050 will be small. An estimate of net increase is 120 Mha that is essentially restricted to developing countries, and mostly in SSA (64 Mha) and LA (52 Mha) (Nachtergaele et al., 2012). Intensification will increase annual harvested area, taking "effective" land increase to 160 Mha. On a world basis, 15% of arable land is irrigated and currently produces 42% of all crop production. That is expected to increase little by 2050 (16 and 43%, respectively). Corresponding figures for developing countries reveal a similar relative small expansion in irrigated area (19–20%) but with a static contribution to production (47%). Irrigation is seen, however, to be a relatively more important contributor to production in developing rather than developed countries.

Given that anticipated expansion of cropping area to 2050 is small, amounting to 10% when intensification is included, the target of 70% greater production required to feed a population of 9.2 billion by 2050 can only be met with a substantial increase in yield. Evolving systems must be more productive than existing ones to meet that challenge. To be prudent, we propose seeking "proof of concept" with at least proportional increases during the intervening period, *e.g.* 50% increase by 2025. If during the period to 2050, a greater proportion of cropland is devoted to biofuel and other non-food crops, then even greater yield of food crops will be required to meet global demand.

Area devoted to biofuel crops in 2009 was small (*ca* 36–41 Mha) (Fischer, 2009; Liska and Perrin, 2011) while predictions of future expansion are difficult because they depend largely on future political decisions and relative prices for food and energy. UNEP (2009) report projections of 60–80 Mha, or even 166 Mha, by 2020, which are equivalent to 4%–11% of the current stock of arable land. Meanwhile political decisions already in place continue expansion of food crops for biofuel, *e.g.* sugarcane and maize for ethanol in Brazil and USA, respectively, and soybean and oil palm for biodiesel in Argentina and Indonesia. Decision makers do not appear to understand the enormous impact that biofuel production will have on an already precarious situation of food security. A simple concept such as SNU can help here. When grain is used to produce ethanol, the amount needed to feed a person well for one year will produce just 200 l (500 kg at 0.4 l/kg), equivalent to 140 l gasoline (Connor and Mínguez, 2006), sufficient to fill the tank of a modern family car on two or three occasions. Proposals and current actions to solve the impact of biofuel on food security by switching to non-food crops (*e.g.* Jatropha) are misguided because they too require land, water, and nutrients that could be used for food production. Crop residues (cellulose) offer the best potential for fuel, but only to the extent that removal from cropped fields does not impair soil structure or fertility beyond what can be redeemed by management and fertilizers. Summaries of recent field studies show that soil organic matter is consistently lost when crop residues are removed at high rates but there is large variability in results and continued, long-term studies are needed to quantify changes associated with harvest of crop residues (Karlen et al., 2012).

4. Limits to crop yield

Globally, average yields of major crops have increased steadily during the past 50 yr due to a combination of plant breeding and improved agronomic management. Results for major staple crops, presented in Fig. 2, show linear increases that other studies (Duvick and Cassman, 1999) reveal have been sustained at continuously increasing investment in plant breeding. As yield has increased, relative (%) gain has decreased, causing concern in some circles, especially as evidence accumulates of possible plateauing of yield in some high yielding systems (Grassini et al., 2011). That should be expected, however, as yield increases towards an inescapable attainable maximum, determined, at each site, by interaction of genotype with environment. Just what that attainable yield is and how it controls currently existing

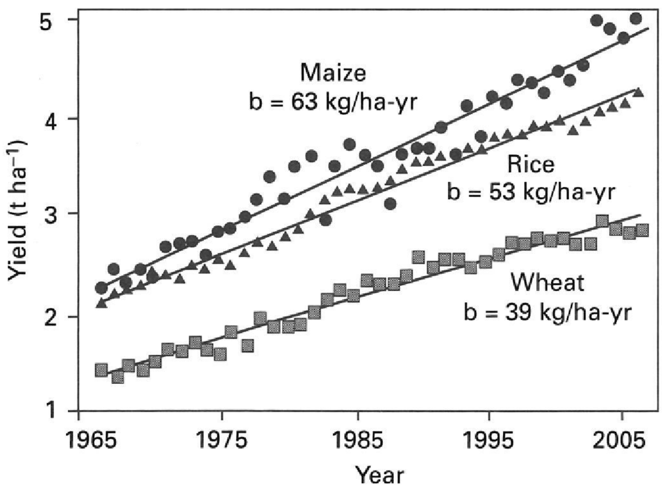

Fig. 2. Progression of average world yield of maize, rice, and wheat during the period 1965–2007 (data from FAOSTAT).

"exploitable yield gap", the difference between attainable and actual yields, at each location, is currently a matter of intensive investigation (Cassman et al., 2003; Fischer et al., 2009; Lobell et al., 2009; Grassini et al., 2011). Given the limited opportunity to extend irrigation, it is not realistic to calculate yield gap for all locations against "potential" yield obtainable with adequate supplies of nutrients and water. Such calculations (*e.g.* Foley et al., 2011) overestimate opportunities to increase crop production. Three questions arise. First, are current trends in yield gain sufficient to provide the additional production required by 2050? Second, if so, what chance to maintain them? Third, if not, what options to increase the rate of yield gain.

There are answers to these questions in relation to an additional production of the 1000 Mt of grain required by 2050. Take, for example, the global average cereal yield data in Fig. 2. If current rates of gain could be maintained for 37 years on current crop area then production could increase by around 980 Mt—not quite enough, and a risky proposition! Additional area and/or more intensive cropping would be required to meet demand. Bruinsma (2009) provides detailed regional analyses of that scenario and finds a solution in which 90% and 80% of required increase is achieved by a combination of yield gain and greater cropping intensity in developed and developing countries, respectively. The remainder would be achieved by expansion of cropped area. Part of this would be a small (32 Mha, 11% of current) increase in irrigated area but a 17% increase in harvested irrigated area overall. Almost all expansion in developing countries would occur in SSA and LA, presenting new challenges for new combinations of environments and soil types. Two important provisos to this scenario require comment.

First, in some of the world's most productive cropping systems, yields have been stable for many years (Cassman et al., 2010; Grassini et al., 2011). Rice in China, wheat in northwest Europe, and irrigated maize in the USA are among the most notable examples. There is evidence that this occurs because average farm yields are approaching a yield ceiling. This can be either a biological limit of current cultivars or an economic one as occurs, for example, when farmers reduce fertilizer input to maintain profitability. As this effect expands in future, it must be offset by higher rate of yield gain, above historical trends, in remaining production areas. Second, intensification and expansion of cropping in developing countries must pay urgent attention to the many aspects of modern agronomy in both irrigated and rain fed systems, access to and use of inputs, storage and sale of products, and how these changes best apply to small-holder farms. Special attention is required to provide access to fertilizer and advice on its proper management, particularly that of nitrogen. Whereas the green revolution in Asia has increased food production at rate greater than population, Asia now accounts for 65% of world N fertilizer use, proportionate use in SSA remains less than 3%. Substantial increase in fertilizer use is needed to support a "green evolution" in Africa.

Conclusions from this analysis must be

- Success relies on maintaining, at least, the current rate of yield gain; otherwise increased production would require even more expansion of cropping, threatening conservation areas and presenting great challenges for high productivity on marginal land.
- Greater than existing effort and Government support will be required not just to maintain scientific and technical innovations that farmers will require, but also infrastructure and services needed to apply them in developing countries.
- Attention is needed to other aspects of the food production–food demand–food utilization chain to seek efficiencies where possible.
- Expansion of cropping systems of lower productivity, for whatever reason, would simply make the task more difficult and potentially impossible.

Concern that current rates of yield gain cannot be sustained leads others to argue justifiably for the need for even greater investment in yield improvement to be found in significant modifications to plant form and metabolism, including, for example, reengineering photosynthesis for greater intrinsic growth rate and yield potential (Zhu et al., 2010). To this we would add improved agronomy that is needed if genetic potential for greater yield is to be realized. To date, gains in potential crop yield have been achieved largely through greater partition of growth to yield (higher harvest index) rather than increasing intrinsic growth (photosynthetic) rates. Nature has been challenging photosynthesis for millennia and different systems have evolved. Biotechnology is now adding new techniques to crop improvement that increase available genetic diversity in germplasm and accelerate breeding progress. This gives hope that major developments, such as reengineering photosynthesis or improving root structure and function, for a step change in yield gain may also be possible. A recent analysis (Hall and Richards, in press) identifies some opportunities for yield gain in current irrigated and rain fed systems but is pessimistic that current rates of yield gain can be sustained. With regard to possible contributions from major genetic shifts to plant form and metabolism it cautions on the question of timescale. Even if success were possible it would likely take decades, not years, and so be too distant to resolve the urgent requirement for early yield gain. It may turn out that the combination of short-stemmed cereals and nitrogen fertilizer that gave us the first green revolution was a unique opportunity.

So the conclusion must be that success in feeding the world by 2050 presents a major challenge for mankind. The positive attitude to meet this challenge requires greater effort than at present to develop the better cultivars, agronomic inputs, and technologies for farmers, especially those in developing countries, where population growth will occur and consumption will increase. A sense of urgency, not presently evident in the global political landscape, is required to at least maintain current yield gain but also to increase it wherever possible. Greater yield of agriculture remains the best way to save land for nature (Waggoner, 1994).

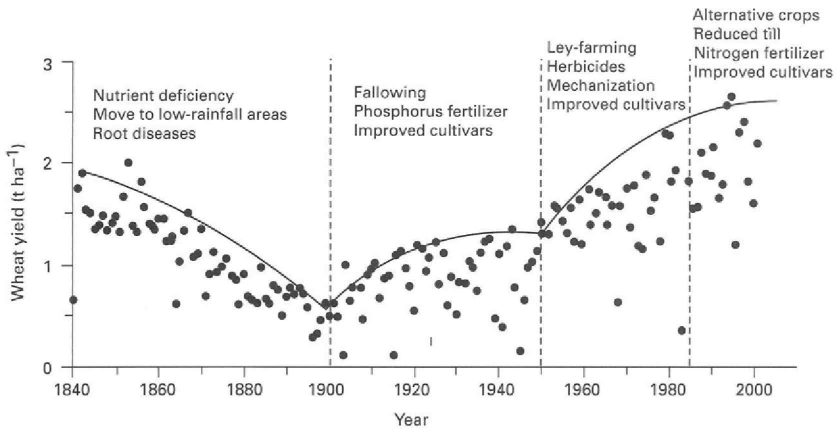

Fig. 3. Progression of cropping strategies and average yield during development of the wheat industry in the State of Victoria, Australia (Connor, 2004).

5. Evolution of cropping systems

Where new knowledge and technology is available, agricultural and cropping systems undergo constant change as farmers apply them to respond to changes in economic, social and climatic environments. Consumers want new products, generally at lower prices; farmers seek to meet those requirements at greater productivity so their standard of living can also increase. There is no such thing as "conventional" production—change is an essential feature of agricultural systems even when the major products remain relatively constant.

An example that sketches yield gain of wheat since inception of the industry in the State of Victoria, Australia, is presented in Fig. 3 (Connor, 2004). The area is semi-arid with winter–spring rainfall, so yield is small and highly variable. The figure presents average yield for each year and records the historical trend relative to major changes that have been introduced to production systems. Farmers started with continuous wheat without inputs, then introduced an alternate fallow year, and later applied phosphorus (P) fertilizer. Then they adopted a radically new system of wheat grown in rotation with leguminous pasture grazed by sheep to capitalize on a boom in wool prices and the synergy within legume–cereal rotations. When the value of wool collapsed, however, farmers replaced the crop-pasture (ley-farming) system with tactical sequences of wheat, oilseed and legume crops, and limited use of fallow. Yield responses were achieved along the trajectory of change.

Refinements were added continuously, *viz.* improved wheat cultivars, new crop sequences, herbicides, new formulations of P fertilizer, N fertilizer, integrated pest management, integrated nutrient management, transgenic crops, reduced and zero tillage, improved machinery, monitoring systems for optimal use of fertilizer, *etc.* Where-to-next was always a question and remains an issue. Higher prices for wool could lead to a new crop–sheep system. Higher prices for crops would confirm their current dominance. But the system will never return to its organic origins of unfertilized wheat, continuous or in rotation with fallow, because those systems have been shown unable to sustain adequate productivity.

All farmers did not adopt the management changes described in Fig. 3 synchronously. There were leaders and laggards: innovators and followers. Adoption on individual farms was determined by economics but also by lifespan of current equipment, generational change of managers, and aggregation of farm units. There was not always an agreement within communities of the most appropriate system and indeed each new option was not equally appropriate to every farm. Gradually, though, transiently dominant systems became established. Farmers are innovators and have tested many other strategies that did not succeed: other pasture combinations, wool-less sheep, llamas, native fruits, new food crops, organic crops, biofuel crops, and agroforestry. Many are now the talk of revolutionists.

6. So what is the revolutionary option?

A distressing feature of present day discussions of food security is the influential support provided by various Government and International Organizations on the need for radical transformation of agricultural production methods for various environmental and sociological goals. In these, inadequate attention is paid to global food security, so the conclusions are misguided. Here we draw attention to two recent examples.

First a book (Trueba and MacMillan, 2011) that has its origins in FAO and gains substantial support with a strongly positive foreword by its then incumbent Director General. It presents the current hunger of 1 billion fellow humans as an emotive backdrop to the challenge of feeding humanity. The authors contend that success will require radical transformation of food production systems because current methods have, in large measure, fueled all five components of the current global crisis. These are current hunger, climate change, energy, environmental degradation, and economic/financial crisis. The authors identify the link between agriculture and these component crises as its current dependence on fossil fuel energy that promotes a form of agriculture that produces and inadequately distributes food at high and volatile price, causes environmental degradation and climate change, and contributes to the present global financial chaos. They assure readers, however, that there are good precedents upon which to build such new production systems that will be sustainable.

The examples provided are agro-forestry, organic farming, multi-storey cropping, conservation agriculture/zero tillage, and sustainable rice intensification. Conservation agriculture/zero tillage apart, because this is a method of soil management widely applied and applicable to many production systems, especially in modern agriculture, the proposed changes are all to low input systems. They are chosen to be less dependent on fossil fuel energy and more dependent on natural biological cycles. The consequences are twofold.

First, these systems are much more demanding of human labor and, largely as a result of low nutrient supply, are less productive than modern agriculture. Second, with agriculture transformed in this way, more land would be required to feed the world. More land is required not just to offset lower yields of individual crops but also to provide the organic nutrients in raw or composted plant biomass or in concentrated in animal manure that the system requires.

Claims for high productivity of organic agriculture (Badgley et al., 2007) and the rice intensification system (Stoop et al., 2002) have been discredited (Doberman, 2004; Sheehy et al., 2004; Smil, 2004; Connor, 2008). A recent article (Seufert et al., 2012) does not change these conclusions. It compares yields of individual crops grown, respectively, with high inputs of organic or mineral nutrients and is not a comparative analysis of organic and conventional agriculture. It is the cost of organic nutrients (plant biomass or manure) and biological N-fixation comprising land, time, labor, water, and other nutrients that most disadvantages organic agriculture and lowers system production well below that of conventional agriculture.

In fact, agriculture uses a small proportion of total energy. In developed countries, indirect and direct use to the farm gate is around 2% of national energy, while the remainder of the food system, through to consumption, consumes a further 8–15% (Gifford and Millington, 1975; Pelletier et al., 2011; USDA, 2006). There is plenty of opportunity for society to reduce energy use in other optional activities before shortage might force them to return to the fields to produce their daily bread. Mechanization and fertilizers are keys to feeding a large and complex society and food need not always be as cheap as now. Farmers should, of course, as the rest of society seek greater energy-use efficiency and there is ample evidence that they are achieving it in large measure adopting such practices as zero tillage in many important agricultural areas. Fertilizers, although energy intensive to produce, do contribute significantly to greater energy-use efficiency in farming because they support high yield over large areas. There will always be sources of energy and agriculture will have priority because it is an essential activity.

A second case for comment is the recent Foresight exercise of the European Commission's Standing Committee on Agricultural Research (SCAR) (EU, 2011). Faced with the challenge to advise on research strategies to best feed the world by 2050, while preserving the agricultural resource base and nature itself, the authors base their considerations on two "narratives". First, the "productive" narrative is presented as the current dominant agricultural production paradigm, while the second, the "sufficiency" narrative, is a low-input alternative. The authors present these extremes, as guiding paradigms, to assist discussion of future development and research requirements. However, the definitions are too narrowly defined for the dominant "productive" narrative and too widely defined for the alternative "sufficiency" narrative. They set the current paradigm of modern agriculture as a straw man that is easily knocked down.

The real world is different. The dominant paradigm, from which the report recommends transition to a more sustainable system, is not the production-at-all cost, ignore-social-inequality and resource constraints that the text describes. In reality the dominant narrative is a wide mix of activities in which farmers are continuously adjusting, as in the example presented in Fig. 3, to technological, economic, ecological, and social forces. Further, the report unreasonably attributes many adaptive features of modern agriculture to the "sufficiency" alternative that places success in a combination of "agro-ecological options and behavioral change". Those options, integrated pest management, integrated nutrient management, and conservation tillage, are not only some of the important adaptive features of the dominant paradigm, but were invented and developed within it. The only defensible distinguishing features of the real "sufficiency" narrative, as it applies to production methods, are no use of transgenic cultivars, little or no use of chemical fertilizers and pesticides, and low productivity. There is precedent for this approach to defining alternatives in agricultural production systems (NRC, 1989). In that early major tome, "Alternative Agriculture" was described as the province of those who care about and promote biological integrity of agricultural systems while modern agricultural was that using excessive amounts of agrochemicals. NRC's proposed alternative methods were also conservative practices employed by many farmers at the time.

The significant failing of the "sustainability narrative" is its low productivity that the authors do not confront. They disregard extensive literature, some referred to above, that records and explains the problem. They defend their position with reference to an unpublished Social Ecology Working Paper from Klagenfurt University, Vienna, reporting that organic agriculture could feed the world, and a misinterpretation of a major study (Pretty et al., 2006) that reports relative yield gains from "agro-ecological" interventions in cropping systems in various developing countries. It is true, as the Foresight exercise reports, that analysis of 286 projects in 57 countries involving 12 million farmers on 36 Mha shows increased productivity by an overall average of 79%. This does represent some success, but not enough. Inspection of the data reveals that that the high value was achieved because yield gain was greater (average *ca.* 200%) in many low yielding (<1 t/ha) crops of maize, millet and sorghum. These are the crops of resource poor farmers of SSA and LA. Yields much greater than 1–2 t/ha are needed to resolve food shortage there, showing that crops cannot be adequately fertilized by residue management. Large areas cannot be excluded from food production, or their soil nutrients exported in biomass or manure, to provide the required organic nutrients for remaining cropping fields. The maximum yield of rice without intervention in these data was 7–8 t/ha, but intervention of lower yielding crops only approached this level in one of many comparisons. "Agro-ecological" interventions are a useful preliminary step in the search for greater yield but they cannot be reasonably presented as a way to achieve the greater production that will be needed in future. Overwhelming evidence is that production would fall below current levels.

These two examples highlight the polarization that prevents productive discussion on how best to feed the world and preserve nature. Now is the time to move away from ideologies, emotions and narratives, and embark on comprehensive analyses of complete agricultural production systems. Studies, following thermodynamic and stoichiometric principles, are required of interactions of land and food production with quantitative considerations of impacts of inputs of water, nutrients, labor, time, money, energy, knowledge and technology expanding, for example, the approach used recently by Tilman et al. (2011). In the case of organic and low-input systems, it is essential to include consideration of the land and time needed to provide organic nutrients or fix N_2. The issue is the analysis of systems, perhaps, and not individual crops. Focus on individual crops continues to confuse discussion about the productivity of organic systems (Connor, 2008).

7. Towards 2050

Already, as of 2010, 50% of world population lives in urban areas and that is expected to rise to 65% by 2050. In future, an increasingly smaller proportion of farmers will produce food for the majority.

The requirements for global food security by 2050 demand continuing evolution of the current paradigm to provide both sufficient food and to protect the resource base of agricultural and non-agricultural environments. The former by increasing production on essentially currently cropped area by combining higher yields with intensified cropping. The latter by careful and efficient use of resources that will preserve the agricultural resource base and prevent leakage to non-agricultural ecosystems. Intensification of cropping will contribute more than expansion of area.

This continuing evolution requires that unrealistic hopes of low-input agriculture be put aside and false hopes of organic agriculture be strongly contested. EU (2011) places priority emphasis on approaches that promise building blocks towards "low-input high-output systems that integrate historical knowledge and agro-ecological principles that use nature's capacity." Stoichiometry and thermodynamics of crop growth regarding nutrients, water and solar radiation advise us that this is not possible. Low input agriculture, forced on poor farmers by economic circumstance, or advised by misguided NGOs, is not the solution for developing countries. Productivity is small and decreases as nutrients are mined from the soil (Henao and Baanante, 2006). Productivity is inadequate to provide a reasonable life style for current inhabitants so the systems will only continue to sustain "poverty and malnutrition" (attributed by Taverne, 2005 to C.S. Prakash, Indian Plant Biologist). Certified organic agriculture will remain a small part of global food production (now < 1%) in places where there is a combination of good supply of organic nutrients and a market prepared to pay higher prices for the products.

The challenge to continue the evolution is, however, considerable. It will require attention to pressing problems of productivity, efficiency, resource conservation, and ecological impact. In fact many of the research priorities are the ones presented by the "revolutionaries", but without a fixation on low inputs and other restrictions of organic agriculture. The latter, including denial of both biocides and transgenic cultivars for control of biotic stress, guarantees yield loss and high labor requirement. The future must be a more intensively scientific and technological agriculture, one that measures conditions of soils, crops, and animals and manages them efficiently and respectfully. Technology is also crucial to resolve environmental challenges introduced by intensification. Nitrogen management is a case in point. Nitrogen is required in large quantities for high yield and is extremely mobile in the environment. Crops are best provided with N fertilizer through their growth cycle at rates they need and can use. This is most feasible with inorganic sources using current delivery systems and methods of detection of crop nutrient status. Food safety must be a given, to which quantity and quality are added in turn. Food hazards include physical, chemical and biological agents, introduced during production, transport, or processing. In future, all food will be traceable, via its route to market, to its place and method of production. None of these activities is new. They already exist in the current dominant paradigm: the issue is to extend them. Food has never been safer than now, and it will be increasingly safe in future.

There are, however, aspects of societal behavior, outside agricultural production systems, that can assist achievement of adequate food for all by 2050. Global demand for food could be reduced by less waste and by modifying diets and so assist meeting food demand by 2050. These deserve comment.

Food waste occurs along the entire food supply chain, and is especially significant for fresh fruits and vegetables, milk products and meat, and for other items at meal tables also. It is estimated that losses totaling 30–40% occur in both developing and developed countries but in different ways (Smil, 2001; Godfray et al., 2010; Foley et al., 2011). In developing countries most loss (25–35%) is on-farm or during transport and processing. In developed countries, by contrast, loss during those stages is small, just 12–16%. The major loss (18–24%) is associated with final preparation and consumption. In developing countries better on-farm storage and transport would reduce losses. In developed countries, cheap food, excessively cautious labeling for health and quality reasons, and large meals used as a competitive edge between restaurants, all encourage waste. In urban societies, unlike rural counterparts, the food chain mostly stops at the table so uneaten food is discarded without opportunity to become animal fodder for further production of human food. Losses of 10–15% of some items may be unavoidable suggesting that reduction of waste to base levels in developed countries could reduce food demand by 100 Mt grain (Smil, 2001). On a global basis, reducing waste towards base levels could reduce demand for food by perhaps 10%. Here is a significant potential contribution to help reduce the global food demand.

With regard to diet, one commonly presented option to reduce global food demand is smaller consumption of meat because, except for ruminants grazing entirely of grass, production of meat by mono-gastric animals, principally swine and poultry, is more demanding of primary productivity than is vegetable protein. Grain–meat conversion ratios differ among species and production systems but typical values are of the order of 2.2, 3, 3, and 8 for fish, swine, poultry and beef cattle on grain rations, respectively (CAST, 1999). These numbers explain the now large imports of grain into increasingly affluent China for feeding mostly swine and poultry. The potential savings available by reducing meat in diets are not, however, as large as might be expected from these ratios. First because animal fodder also contains components that are not edible by humans, and in the case of lot-fed beef, which receives much comment, the life-cycle conversion efficiency, taking into account time spent grazing pasture and fodder crops, is essentially that of swine and poultry (CAST, 1999). While the conversion ratios reveal that major dietary change away from meat would reduce primary food demand significantly, social engineering of diet is probably better applied to dissuade over consumption and achieve well-balanced diets of energy, protein, vitamins and minerals for all.

8. Discussion

There is no revolution alternative; there are no new systems to which urgent transformation is required. The dominant paradigm, modern agriculture, covers the range of options available and is evolving to meet demands of production and environmental conservation. It is disadvantageous to discussion, and hurtful to the majority of farmers, to describe modern agriculture pejoratively as some form of "industrial" activity that thinks only of yield and profits. It is a fabrication used to defend an argument for radical change that, if accepted by many in our society who no longer have contact with food production or rural environments, would complicate the major challenge facing humanity—how to feed a growing population.

Greater yields, along with intensification, on essentially the same cropped area can best provide the required productivity and, at the same time, save land for nature and other uses. There are many scientific, technological, and socio-economic aspects to the challenge, so many solutions will be required to meet site- and society-specific requirements. Ability to maintain the current rate of yield gain into the future is not assured. Failure would require major expansion onto currently uncropped areas and conflict with nature conservation and other land uses. Governmental and International support must be greatly increased not just to develop and maintain scientific and technical innovations that farmers will require, but also infrastructure needed to apply them, especially in the varied socio-economic settings of developing countries. This will require major investment in research on plant and animal improvement, pest and disease control, monitoring of crops and livestock for improved management of agricultural systems adapted to individual regions and farm-types.

Waste reduction and dietary change can play a role in reducing the required increase in food production. And there are good reasons to promote both for their own values but contribution to reducing food demand will be small compared to the required increase (70%) in production. Success in this is the major challenge of our time. In our view it is more imminent and beats global warming by a large margin and yet by comparison governments around the world are less convinced. The cost to develop and maintain sufficiently productive systems that are environmentally acceptable will be great. A sum of $100 billion has been mentioned (EU, 2011), very large except when compared with the cost of weapon systems and wars. Rather, governments have other emphases for the future and, with large subsidies for and mandated use of biofuel, have set the stage for serious competition with production of human food. Green fuel for cars currently receives more attention than food for the future.

9. Key points

World food supply must increase by 70% to feed a population expected to grow to 9.2 billion by 2050. The largest increases are required in current developing countries where population growth will overwhelm small declines in current developed countries.

Greater food production can only be obtained, without expansion of currently cropped area of 1500 Mha, by combinations of greater yields of individual crops and more crops per year. This requires greatly increased investment, than at present, in plant breeding for greater yield potential and agronomic management to achieve it within sustainably intensified cropping systems. Expansion of low-input-low yield systems cannot contribute to the solution.

A major challenge is to maintain the current absolute rate of yield increase of major staple crops as yields inevitably move closer to their genetic potentials. There is reason for concern that this cannot be maintained without some new genetic modification to plant metabolism or growth processes.

Failure to maintain yield gain will increase pressure for expansion of cropped area, including into marginal areas, at expense of conservation of land for nature and its other uses.

Demand for food can be reduced by minimizing the considerable waste that occurs along the food chain, in both developing and developed countries. Success in developed countries could reduce food demand by 10% and significantly reduce pressure on food production.

Dietary change, although promoted by some, will contribute less as developing countries improve diets and increase meat consumption. Education to reduce over consumption and achieve more balanced diets everywhere is more likely to reduce food demand while contributing to human health.

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